

Influence of Low Energy Hadronic Interactions on Air-shower Simulations

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Experiments measuring cosmic rays above an energy of $\sim 10^{14}$ eV deduce the energy and mass of the primary cosmic ray particles from air-shower simulations. We investigate the importance of hadronic interactions at low and high energies on the distributions of muons and electrons in showers on ground. In air shower simulation programs, hadronic interactions below an energy threshold in the range from 80 GeV to 500 GeV are simulated by low energy interaction models, like FLUKA or GHEISHA, and above that energy by high energy interaction models, e.g. SIBYLL or QGJSJET. We find that the impact on shower development obtained by switching the transition energy from 80 GeV to 500 GeV is comparable to the difference obtained by switching between FLUKA and GHEISHA.

1. Introduction

Cosmic rays at very high energies ($E > 10^{14}$ eV) can be measured only indirectly by observing extensive air showers in the atmosphere. Ground based air shower arrays in this energy range observe the distribution of particles on observation level to deduce the mass and the primary energy of the initiating particle. The relation between the measurements and these quantities can be inferred only from simulations of the development of the air showers [1].

The present implementations of interaction models cannot describe all observed air shower properties with a good precision. For example, at the Pierre Auger Observatory, the observed number of muons is underestimated in simulations with commonly used hadronic interaction models [3]. The uncertainties in predicting shower properties are mainly a consequence of uncertainties in the modeling of hadronic interactions, since these cannot be obtained directly from QCD calculations.

Phenomenological hadronic interaction models are needed for describing particle interaction properties over a wide range in energy, including phase space regions and energies, which are presently not covered by particle physics experiments. The energies of the first interaction in high energy showers are not accessible by current

accelerators. At low energies there is a lack of precise data in the forward region, which is relevant for air shower development [4].

2. NA61/SHINE Experiment

Among the accelerator data results, the minimum bias analysis of p+p and p+C [6] collisions at a beam momentum of 158 GeV/c, delivered by the NA49 Collaboration, provided information about the inclusive production of charged pions, which have been already used to improve the precision of air shower simulations [7,8]. The NA61/SHINE apparatus is an upgrade of the large acceptance experiment NA49 [9]. A new time of flight detector in the forward beam direction has been installed and tested, increasing the accuracy of the particle identification. The update of the DAQ and of the readout of tracking detectors provides an increase of the maximum detection rate by a factor of 10 with respect to NA49. In 2009 the data taking program for NA61/SHINE contains π +C interactions at energies of 158 and 350 GeV.

3. Air-Shower Simulations

The particles from air showers arrive at the observation level extending over a large area of several hundred meters to kilometers, with the maximum particle density near the air shower axis.

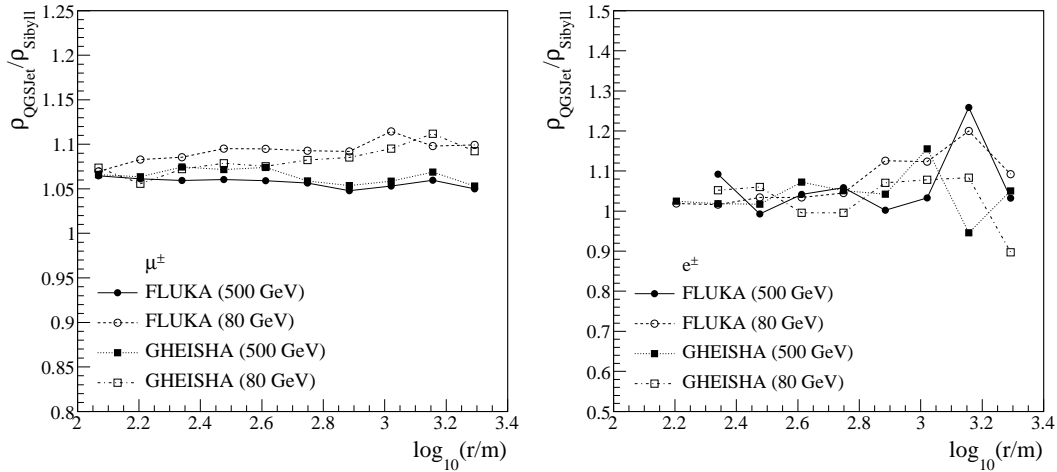


Figure 1. Lateral distribution of the ratio of number of muons (left) and electrons (right) between QGSJET and SIBYLL. The same hadronic interaction model is used for describing of the hadronic interactions below the transition energy indicated in brackets.

To predict the lateral distribution of particles one needs to know the interaction cross section with the air nuclei, and the properties of the final state produced in such an interaction, namely the multiplicity, composition and momentum distribution of the final state particles. While the high energy interactions are of direct relevance to the longitudinal shower development [10], the particle production at low energy is important for the lateral distribution of shower particles at ground. The use of different hadronic interaction models for low-energy interactions leads to significant differences of the predicted particle distributions [11]. The electromagnetic particles, originating from π^0 decays, bremsstrahlung and e^\pm pair production with a small component from μ^\pm decays, are well described by QED. The muonic component, produced mainly in decays of charged pions (95 %) and kaons (3-4 %), depends upon the hadronic models used.

To investigate the importance of hadronic interactions in the NA61/SHINE beam energy region for ground-based shower observables we performed simulations with different interaction models and varied the transition energy between the low- and high-energy models. Using CORSIKA [15], eight sets of proton show-

ers of 3.16×10^{18} eV with a uniform $\cos(\theta)$ distribution, θ being the zenith angle ranging from 0 to 60 degrees, were generated. The sets are built by combinations of generators describing the low energy hadronic interaction, FLUKA [16] and GHEISHA [17], and generators describing the high energy hadronic interactions, QGSJET II [7] and SIBYLL 2.1 [18]. The transition energy between the models is taken to be 80 GeV or 500 GeV. EGS4 [20] is used for the simulation of electromagnetic interactions.

To make a direct comparison of the number of particles predicted with different assumptions already with 100 showers, shower-to-shower fluctuations have to be eliminated as far as possible. Most of the fluctuations in the shower development, and thus in the number of particles, originate from the fluctuations in the first few interactions. Therefore, the first interaction in the simulated ensembles are preselected to have a secondary particle multiplicity larger than 1000 and an inelasticity of at least 0.85. This is achieved by pre-simulating air showers with CONEX [21] using QGSJET II and selecting showers with the suited characteristics of the first interaction. The secondary particles of these first interactions are then fed to CORSIKA to generate the corre-

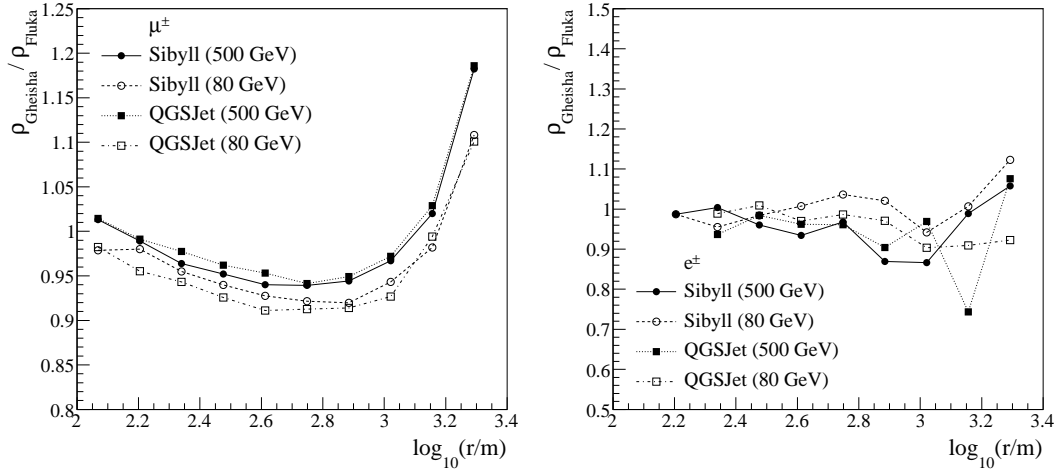


Figure 2. Lateral distribution of the ratio of the number of muons (left) and electrons (right) as predicted by GHEISHA and FLUKA. The same hadronic interaction model is used for the description of the hadronic interactions above the transition energy indicated in brackets.

sponding air showers.

The differences between QGSJET and SIBYLL for the predicted number of muons and electrons arriving at ground level as a function of the logarithm of the distance to the shower axis are illustrated in Fig. 1. The range in lateral distance for the figures is chosen such that the particle densities on ground are larger than 10^{-3} particles/m². SIBYLL predicts by 5 to 10% fewer muons with respect to QGSJET over the whole distance to the core. Moreover the ratio of the muon densities is not constant with the distance to the shower axis. Switching the transition energy between the models from 80 GeV to 500 GeV reduces the difference by up to 4%. The density of electrons, as expected, is not influenced by the choice of the model. The difference on the muon/electron densities between the low energy hadronic interactions is shown in Fig. 2. The large dependence on the distance to the shower axis is mainly due to different transverse momentum distributions predicted by the models. At distances larger than 1000 m, which are of relevance to the Pierre Auger Observatory, GHEISHA predicts 5-20% more muons than FLUKA. The proton-air and pion-air cross-sections for the two models are similar in the range 80 GeV to 500 GeV, but still

a 10% effect is visible just by switching the transition energy.

In Fig. 3, we show the ratios of the muon and electron density distributions for the predictions obtained with 80 GeV and 500 GeV as transition energy. The observed difference is a convolution of the parametrization in the high energy and low energy models of the hadronic interactions in the range of 80-500 GeV. The smallest difference of about 4%, constant over the whole distance range, is observed in the case of the QGSJET-FLUKA combination. Any combination between GHEISHA and other models gives a distance dependent difference of up to 15 % at $\log_{10}(r/m) = 3.4$.

4. Conclusions

The effect of the simulation of low energy hadronic interactions on air shower development has been investigated by switching the transition energy between the high- and low-energy hadronic interaction models and by comparing different interaction models. The difference in the predicted number of muons at ground level can be as large as 15 %, which is of the same order as the difference obtained by changing the high-energy hadronic interaction model. Hence

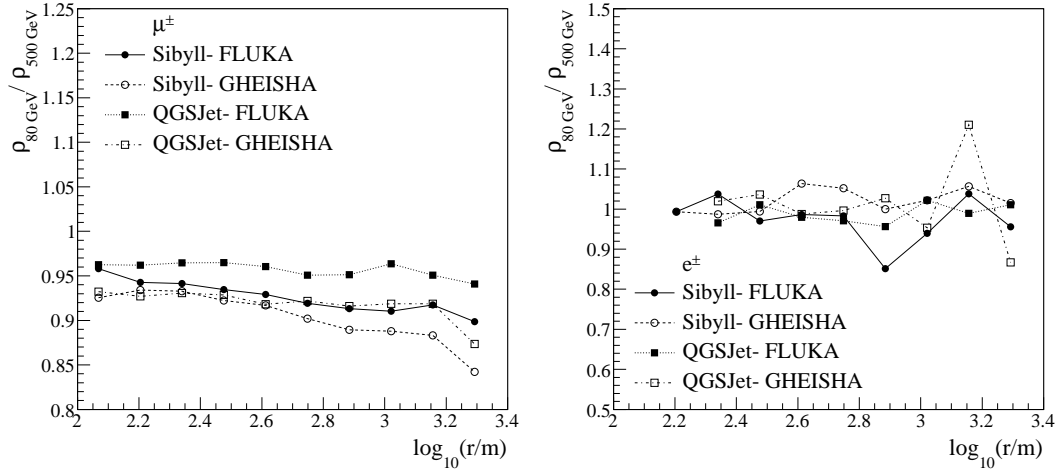


Figure 3. Lateral distribution of the ratio of the predicted number of muons (left) and electrons (right) obtained by switching the transition energy from 80 GeV to 500 GeV.

better modeling of hadron production is needed not only at the highest energies but also for energies up to 500 GeV. The NA61/SHINE data will cover a large region of the forward phase space of low energy hadronic interactions with energies up to 350 GeV for improving the reliability of air shower simulations.

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